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A COMPREHENSIVE APPROACH TO IN-FLIGHT THRUST DETERMINATION.(U)

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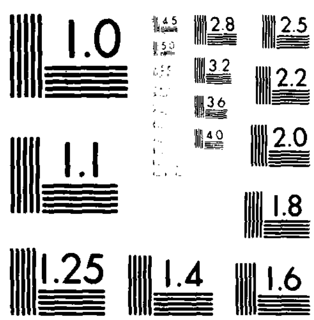

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Technical Memorandum

A COMPREHENSIVE APPROACH TO IN-FLIGHT THRUST DETERMINATION

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Aerospace Engineer

Strike Aircraft Test Directorate

15 February 1980

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A systematic, comprehensive approach was used recently to develop an in-flight thrust computational routine for a mixed-flow, dual spool, augmented turbofan engine with a variable area convergent-divergent exhaust nozzle. To provide an insight for the necessity of this approach, a brief historical background of in-flight thrust measurement is presented and classical nozzle theory is discussed briefly. The development of the computational routine is discussed and some general test planning guidelines are presented.

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PREFACE

The design performance capability of the propulsion system/airframe combination can be substantiated without specific knowledge of propulsion system thrust and airframe drag. However, assessment of departures from the design goals requires the determination of both airframe drag and propulsion system thrust. Although the ability to determine propulsion system thrust during flight continues to be a main contributor to the uncertainty in evaluating aircraft performance, the Navy has continually stressed that accurate airframe drag determination necessitates accurate in-flight thrust calculations. The development of dynamic performance flight test techniques has not altered this position. The difficulties in the accurate determination of in-flight thrust to a high level of confidence has been attributed to the inadequate application of available technology and a lack of attention to detail. A systematic, comprehensive approach was therefore used recently to develop an in-flight thrust computational routine utilizing theoretical predictions, modified by model and full scale engine test data. This memorandum discusses the background, applicable theory, and approach used in the development of this computational routine and provides some general guidelines relative to in-flight thrust determination.

APPROVED FOR RELEASE

L. Wayne Smith

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TABLE OF CONTENTS

INTRODUCTION

GENERAL

1. Various methods for determining in-flight thrust have evolved over the years utilizing direct measurement and indirect computational techniques. The direct measurement technique has generally been regarded as unsatisfactory because the engine should be free from longitudinal constraints. However, this is not practical with normal aircraft installations and attempts to account for forces transmitted through connectors, supports, and engine-to-airframe seals have not been successful. More successful indirect methods have been devised using gross thrust and ram drag. Various techniques have been developed for computing gross thrust during flight based on engine and airframe parameters which can be readily measured in flight. A typical approach has been to identify the appropriate ideal situation (based on classical convergent-divergent nozzle and/or classical convergent nozzle theory and a $W\sqrt{T}$ or AP nondimensional thrust group), which is then used to establish an ideal thrust datum. Appropriate calibration factors or coefficients, which identify the efficiency of the expansion process, are then applied to the ideal thrust to obtain the actual gross thrust.

2. This memorandum presents a recent approach taken in the development of an in-flight computational routine for a mixed-flow, dual spool, augmented turbofan engine with a variable area convergent-divergent exhaust nozzle. To provide an insight for the necessity of the comprehensive approach which was taken, a brief historical background of in-flight thrust measurement is first presented. This is followed by brief discussions of classical nozzle theory including ideal gross thrust and classical nozzle coefficients used to identify the efficiency of the nozzle expansion process. Development of the in-flight thrust computational routine is then discussed and finally some general test planning guidelines are presented.

BACKGROUND

3. The convergent nozzles of early turbojet engines choked at nozzle pressure ratios obtainable during sea level static operation. A single gross thrust coefficient (C_F) could be established from sea level static testing of the airframe/propulsion system on a thrust stand and applied to computed ideal thrust for extrapolation to the higher nozzle pressure ratios obtained during flight. Figure 1 graphically depicts this procedure. Systematic error on the order of 5 percent was generally incurred with this procedure, usually resulting from lack of adequate identification of power extractions/bleed air variations between the sea level static testing and actual flight operation. In addition, inaccuracies in determining the nozzle pressure ratio for some engines contributed to the problem. The ram drag term (which is subtracted from gross thrust to obtain net thrust) was obtained from uninstalled engine calibrations conducted with a calibrated bellmouth to establish the relationship between mass flow and parameters measurable in flight, such as compressor rotor speed and compressor inlet temperature.

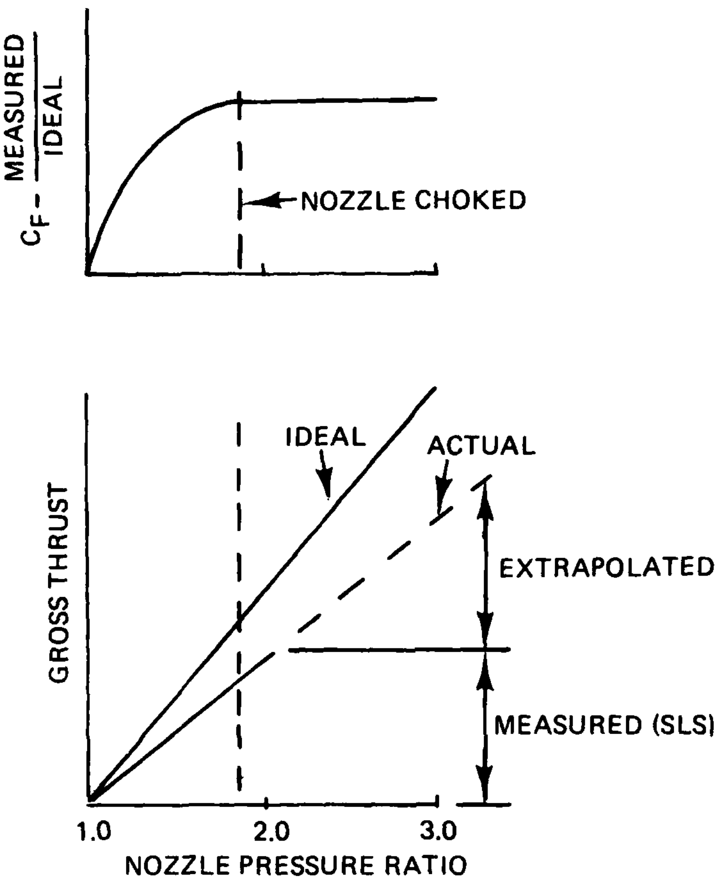

Figure 1
In-flight Gross Thrust Determination
Sea Level Test Stand Method
Convergent Nozzle

4. A second procedure which attempted to measure gross thrust and engine mass flow involved traversing the nozzle exit plan with a swinging rake apparatus in an attempt to obtain total temperature and total and static pressure maps. Investigations involving turbojet engines indicated random errors of ± 3 percent and no known systematic errors. Attempts to apply this procedure to a nonafterburning, convergent nozzle turbofan engine generated doubt as to the validity of the measurements because of asymmetric pressure profiles and disagreement with thrust stand measurements as high as 7 percent. Tests conducted with afterburning turbofan engines were also unsatisfactory because of large pressure and temperature gradients at the nozzle exit. Other problems associated with this procedure include identification of the drag of the swinging rake installation and identifying the effect of the installation on airframe/propulsion system interference drag.

5. With the advent of nonafterburning, convergent nozzle, dual spool, mixed-flow turbofan engines, it was found that the nozzle pressure ratio at which the nozzle choked was not consistent for all flight conditions. It was theorized that the effective throat area of the core (turbojet) engine varied with flight condition due to bypass ratio variations and mixing variations which occurred in the nozzle between the cooler bypass flow and warmer core engine flow. These problems have been less prevalent with afterburning turbofan engines, but problems with accurately measuring nozzle throat areas with variable position convergent-divergent nozzles have been encountered. Problems also have been incurred with establishing nozzle pressure ratios based on total pressure measurements made at the low pressure turbine discharge.

6. In an effort to minimize these problems and reduce uncertainty, the comprehensive approach described herein was used to develop an in-flight thrust computational routine for a mixed-flow, dual spool, augmented turbofan engine with a variable area convergent-divergent exhaust nozzle.

CLASSICAL NOZZLE THEORY

IDEAL GROSS THRUST

7. Indirect approaches for determining in-flight thrust, or net thrust (F_N), are based on the determination of gross thrust (F_G) and ram drag (F_R). Then

$$F_N = F_G - F_R \tag{1}$$

where

> F_G is defined as the sum of momentum and pressure forces at the nozzle exit

and

> F_R is defined as the free stream momentum of the mass flow entering the engine.

Using the above definition, the gross thrust at the nozzle exit plane (station 9) can be expressed mathematically as

$$F_{G_9} = W_9 V_9 + A_9 (P_{S_9} - P_{S_0}) \tag{2}$$

Modern turbojet and turbofan engines are required to operate over a wide range of operating conditions and, therefore, a wide range of nozzle pressure ratios. The minimum nozzle pressure ratio which results in sonic flow at the nozzle throat is identified as the critical pressure ratio. For a convergent-divergent nozzle, operation at pressure ratios below the critical pressure ratio results in overexpansion in the divergent section of the nozzle while operation at pressure ratios higher than the critical pressure ratio results in the flow being underexpanded at the nozzle exit plane.

8. For the ideal situation, the flow is assumed to be one-dimensional, the expansion is assumed to be isentropic, and the specific heat ratio (γ) is usually assumed to be constant during the expansion process. Static temperature, velocity, and area (or static pressure) are calculated based on actual (nozzle inlet) total temperature, total pressure, and mass flow. When the critical ideal nozzle pressure ratio equals the actual pressure ratio, the ideal static pressure at the nozzle throat (the exit plane for convergent nozzles) is just equal to the free-stream static pressure and the ideal velocity at the throat is Mach 1.0. During operation below the critical ideal nozzle pressure ratio, the static pressure of the flow at the throat equals the free-stream static pressure but the velocity at the throat will be below Mach 1.0. This "ideal convergent nozzle" concept is applicable to the ideal expansion process and ideal flow calculations for both convergent and

convergent-divergent nozzles operating at or below the ideal critical pressure ratio. Above the ideal critical nozzle pressure ratio, an ideal convergent-divergent nozzle concept is used which assumes the flow to be fully expanded to free-stream static pressure at the conceptual nozzle exit plan for all operating conditions. This idealization leads to an infinitely variable, flexible geometry ideal convergent-divergent nozzle. The ideal gross thrust ($F_{G_{9id}}$), computed at this conceptual nozzle exit plane (where $P_{S_{9id}}$ is equal to P_{S_0}), is the thrust datum against which actual nozzle thrust is assessed and equation (2) becomes:

$$F_{G_{9id}} = W_9(V_9)id \tag{3}$$

where V_{9id} is the fully expanded velocity of the internal flow. Using this convention, thrust efficiency includes losses both internal and external to the actual nozzle.

9. Other thrust datum conventions may be more convenient for the specific application. A fixed-geometry convergent-divergent ideal thrust datum is based on a fixed design point pressure ratio. Departures of actual thrust from the fixed-geometry ideal thrust would then be expressed at other than design pressure ratios in terms of appropriate coefficients. It is therefore important to have consistent terminology when defining ideal thrust datums so that departures from ideal performance which occur in actual nozzles are identifiable and understood.

10. The form of the mathematical expressions for both ideal convergent and ideal convergent-divergent nozzle gross thrust are predicated on the selection of a "nondimensional ideal thrust group." The selection of a particular group also determines which nozzle coefficients will be used to express the efficiency of the actual expansion process relative to the ideal situation. Two commonly used nondimensional groups are known as the "$W\sqrt{T}$" and "AP" thrust options and are expressed mathematically as

$$\left[\frac{F_G}{W\sqrt{T_t}}\right]_{id} \quad \text{and} \quad \left[\frac{F_G}{AP_{S_0}}\right]_{id} \tag{4}$$

Actually the $W\sqrt{T}$ group does, in fact, have units and, to be strictly nondimensional, would require the denominator to be $W\sqrt{RT_t}$. The nondimensional ideal thrust group is used to develop expressions which are the bases for calculating ideal flow and ideal thrust. Utilizing the nondimensional group simplifies these calculations but mandates using a constant specific heat ratio (γ), which is normally based on the fuel to air ratio and/or total temperature at the nozzle inlet.

NOZZLE COEFFICIENTS

11. Since gross thrust is defined as the sum of the momentum and pressure forces at the nozzle exit, it would seem that the most direct approach for determining gross thrust would be to measure the flow conditions at the nozzle exit and compute gross thrust using these measurements. However, as noted in paragraph 4, attempts to implement this procedure have not been successful. A more accepted procedure is to relate nozzle performance to the flow conditions at the nozzle inlet and compute ideal gross thrust using the ideal nozzle theory discussed briefly in the previous section. The assumptions made in the development of this theory neglect the following salient factors which affect the actual expansion process that occurs in a real nozzle:

a. Momentum losses resulting from frictional losses in the nozzle and nonaxial flow at the nozzle exit.

b. Expansion losses resulting from overexpansion in the nozzle or underexpansion at the nozzle exit.

c. Mass flow variations resulting from flow leaking into or out of the nozzle.

Nozzle coefficients have been empirically developed to account for these factors and are used to obtain actual gross thrust from ideal gross thrust computed for the particular nozzle inlet conditions.

12. The velocity coefficient is a measure of momentum losses expressed mathematically as the ratio of the actual to ideal gross thrust expressed in the $W\sqrt{T}$ nondimensionl group format; the subscript v is used when the ideal group applies to the ideal convergent-divergent nozzle, and the subscript x is used for the ideal convergent nozzle. Mathematically, the velocity coefficients are expressed as

$$C_V = \frac{F_{G_{9act}}}{W_{act}\sqrt{T_{t_{act}}}} \Bigg/ \left[\frac{F_G}{W\sqrt{T_t}}\right]_{id_{con-div}} \tag{5}$$

$$C_X = \frac{F_{G_{9act}}}{W_{act}\sqrt{T_{t_{act}}}} \Bigg/ \left[\frac{F_G}{W\sqrt{T_t}}\right]_{id_{con}} \tag{6}$$

These definitions can be expanded to more meaningful terms since by definition ideal gross thrust is related to the actual nozzle inlet conditions and

$$\left[\frac{F_G}{W\sqrt{T_t}}\right]_{id} = \frac{F_{G_{id}}}{W_{act}\sqrt{T_{t_{act}}}} \tag{7}$$

Making this substitution into equation (5), the velocity coefficient becomes the ratio of actual to ideal gross thrust for the ideal convergent-divergent nozzle

$$C_V = \frac{F_{G_{9_{act}}}}{F_{G_{9_{id_{con-div}}}}} \tag{8}$$

Defining the velocity at the nozzle exit as

$$V_{9_{eff}} = \frac{F_{G_{9_{act}}}}{W_{act}} \tag{9}$$

then

$$C_V = \frac{V_{9eff}}{V_{9\,id_{con-div}}} \tag{10}$$

where V_{9id} is that which is obtainable with an ideal flexible convergent-divergent nozzle operating with no mass flow variations (leakage into or out of the nozzle) and with the actual nozzle inlet total pressure and total temperature. Comparing equation (2) with equation (9), the effective and actual velocities at the actual nozzle exit plane are equal only when the actual static pressure at the exit plane (P_{S_9}) is equal to the free-stream static pressure (P_{S_0}).

13. The flow or discharge coefficient (C_D) applies equally to both convergent and convergent-divergent nozzles and is based on the nozzle throat area (station 8 for a convergent-divergent nozzle and for a convergent nozzle station 9 which coincides with station 8). With no mass flow variation in the nozzle and a given actual nozzle pressure ratio, C_D is the ratio of ideal throat area required to pass the actual mass flow to the actual throat area required to pass the flow. For the same nozzle geometry and pressure ratio, it can be shown that the above ratio is equivalent to the ratio of actual to ideal mass flow; hence

$$C_D = \frac{A_{8\,id}}{A_{8\,act}} = \frac{W_{7\,act}}{W_{7\,id}} \tag{11}$$

14. The gross thrust coefficient is defined as

$$C_G = \frac{F_{G_{9act}}}{A_{act} P_{S_0}} \Bigg/ \left[\frac{F_G}{AP_{S_0}}\right]_{id} \tag{12}$$

For the convergent nozzle, equation (12) can be simplified so that C_G is the product of the convergent nozzle velocity coefficient (C_X) and the discharge coefficient C_D:

$$C_{G_{con}} = C_D \cdot C_X \tag{13}$$

For the convergent-divergent nozzle, explicit expressions for the relationships between C_G, C_V, and C_D vary according to the area used in the F_G/AP_{S_0} group. In general, these expressions take on the form of equation (13) with C_V replacing C_X and will include additional area ratio terms.

15. The nozzle coefficients discussed briefly in paragraphs 12, 13, and 14 all are based on the actual average nozzle inlet conditions, ($P_{t_{7_{av}}}$, $W_{7_{act}}$, $T_{t_{7_{av}}}$), and no mass flow variation during the expansion process. However, mass flow variations from $W_{7_{act}}$ can be expected in the actual nozzle; these variations must be considered when estimating full scale nozzle performance and assessing variations between estimated and actual performance. Three types of possible mass flow variations are discussed below.

16. The exhaust nozzles of high performance turbojet and turbofan engines are usually constructed from sheet metal parts which can be expected to leak. This is particularly true for the variable area, convergent-divergent nozzle constructed using longitudinal conical flaps for both the convergent and divergent portions of the nozzle; overlapping seals are provided along the longitudinal edges of the flaps to minimize leakage. Estimates of the loss of mass flow through the seals are made for the full scale nozzle based on previous experience with similar designs and substantiated from full scale engine tests conducted in an altitude test facility.

17. A second possible source of mass flow variation associated with the construction of variable area convergent-divergent nozzles is depicted in figure 2. The downstream edge of the convergent conical flaps overlap the upstream edges of the divergent conical flaps resulting in a sharp corner at the throat. The flow expanding around this sharp corner produces a local area of low static pressure and, as a result, ambient air flows into the nozzle through a gap at the throat between the convergent and divergent flaps. The gap at the throat is required to permit movement of the convergent and divergent flaps to change the throat and exit

areas. The increased mass flow produces a thrust gain which is not accounted for by either the ideal nozzle or nozzle coefficient theory. The effect of this inflow can be determined from scale model tests. The trend of these effects is used to estimate full scale nozzle performance. Full scale engine testing in an altitude test facility is required to quantify the increment of thrust gained from inflow at the nozzle throat.

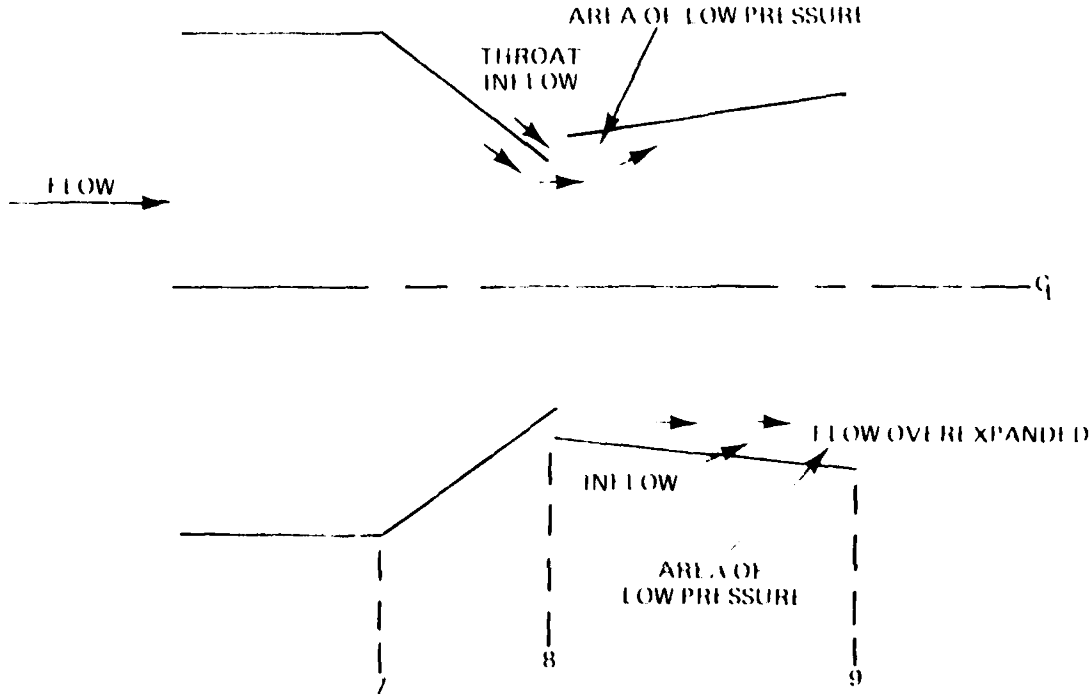

Figure 2
Examples of Flow Variations

18. A third possible source of mass flow variation can occur in the divergent section during low pressure ratio operation when the flow is overexpanded (see figure 2). The longitudinal seals along the edges of the divergent conical flaps are usually located on the inside surface of the flaps to seal with outward pressure. When overexpansion occurs, the flow separates from the inner walls of the divergent section; as a result, the divergent section inner wall static pressure can be less than ambient, the seals pull inward, and ambient air flows into the nozzle. This divergent section inflow cannot be evaluated during the hard wall, scale model testing. Full scale estimates of the incremental thrust gain from this additional mass flow are based on previous full scale engine test experience of exhaust nozzles with similar divergent nozzle flap/seal arrangements; these estimates are substantiated with altitude test facility data of the actual full scale engine/nozzle design.

COMPUTATIONAL ROUTINE DEVELOPMENT

19. A systematic, comprehensive approach was used recently to develop an in-flight thrust computational routine for a mixed-flow, dual spool, augmented turbofan engine with a variable area convergent-divergent exhaust nozzle. The test day, test engine net thrust computational routine basically encompassed the following five subroutines:

a. Nozzle inlet total pressure determination based on measured afterburner inlet total pressure.

b. Nozzle throat area determination.

c. Nozzle coefficient and ideal gross thrust and actual gross thrust determination.

d. Actual engine inlet air flow for the determination of ram drag and net thrust.

e. Afterburner inlet and exit total temperature and specific heat ratio (γ_7) determination.

The first four of these subroutines have provisions to account for engine-to-engine variations.

20. The in-flight computational routine was a contractually required deliverable included in the engine development and performance/durability demonstration program. As a result, development of the computational routine was initiated early in the engine development program. Predicted engine component and overall engine performance was first established based on theoretical analysis, past experience, and gas generator cycle analysis. Model test and component rig tests were conducted to verify and update the performance estimates of the various engine components. Full scale engine tests were conducted at sea level static conditions and two Preflight Rating Test (PFRT) engines were tested in an Altitude Test Facility (ATF). The data base generated from all these tests was used in the development of the in-flight thrust computational routine. Additional ATF test data were used to evaluate the effects of changes which occurred between the PFRT and official Qualification Test (QT) engine configurations, and the computational routine was updated as required. To illustrate this comprehensive approach, a detailed discussion of the procedures used to develop the nozzle coefficient follows.

21. Figure 3 shows schematically the development of each of the pertinent coefficients applied to the ideal gross thrust to obtain test day gross thrust. Predicted gross thrust was first established based on theoretical analysis, past experience, and gas generator cycle analysis. An ideal gross thrust datum was identified and used to establish objective thrust coefficient relationships with nozzle pressure ratio for various nozzle throat areas. Cold flow scale model tests were conducted with five fixed position models covering the entire design throat to exit area ratio operating regime and two prospective area ratio schedules. These tests established:

a. The variation of the flow coefficient C_D with throat area.

b. Momentum losses due to friction and nonaxial flow at the nozzle exit plane.

c. The static pressure distribution over the length of the nozzle.

d. The effect of throat inflow on the gross thrust coefficient (evaluated on one model only).

New gross thrust coefficients were computed using items a and b. Based on these calculations, a "model test modifier" was applied to the "objective C_G." The model tests also established that the thrust gain resulting from the inflow at the throat was greatest at low nozzle pressure ratios where the pressure difference between the throat static pressure and ambient pressure is the greatest.

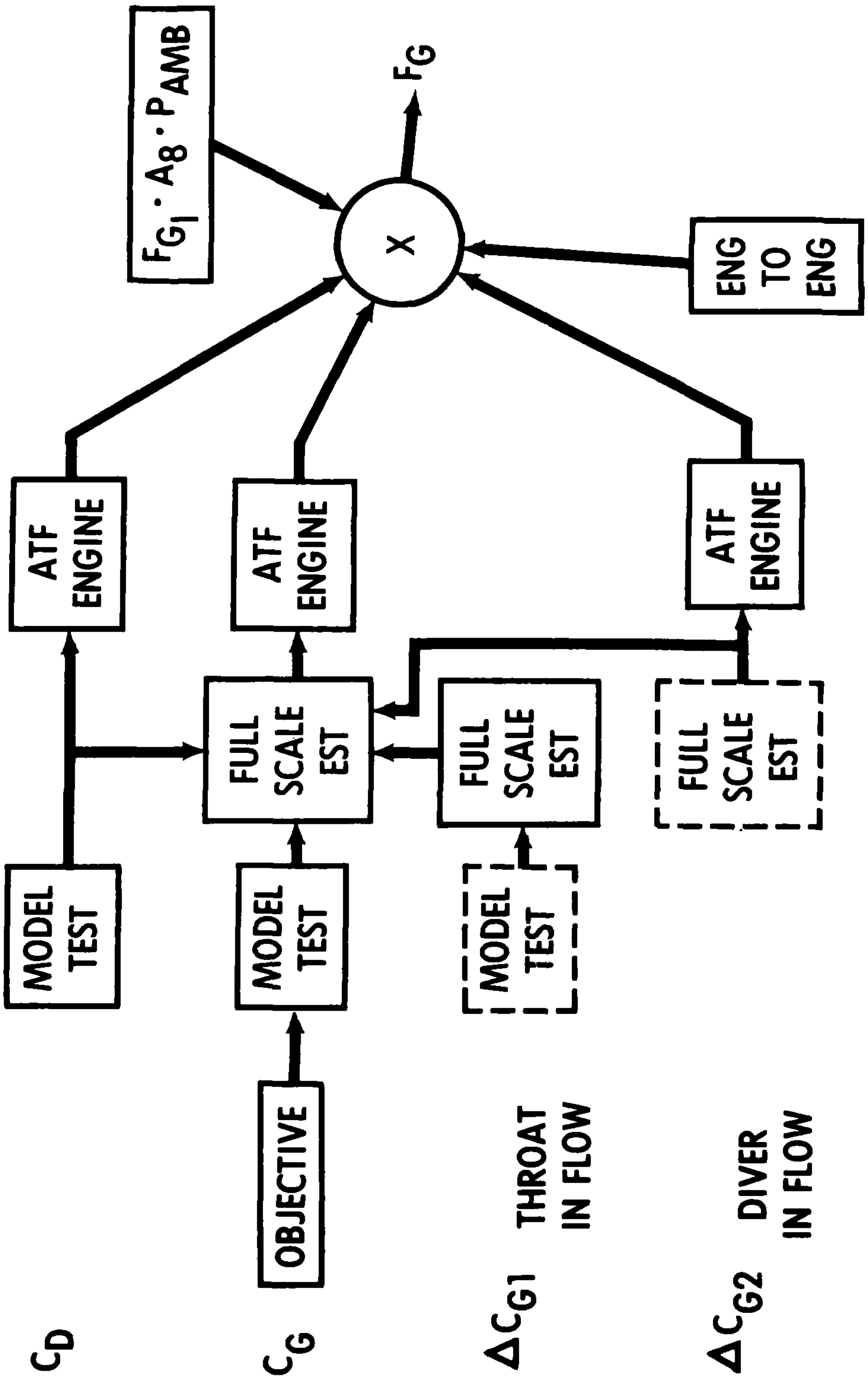

Figure 3
Gross Thrust Computation

22. The momentum loss data were then extrapolated to full scale and used with calculations of ideal exit (V_{9i}) and fully expanded (V_{10i}) velocities (based on the model test flow coefficient data) to calculate estimated full scale gross thrust coefficients. Estimates of mass flow variations resulting from leakage, inflow at the throat, and additional inflow in the divergent section during overexpanded operation were also included in these full scale estimates. Based on these calculations, an "estimated full scale gross thrust modifier" was applied to the previously calculated gross thrust coefficient. Based on full scale engine tests conducted in an ATF, an "ATF engine modifier" was computed and used to adjust the full scale gross thrust coefficient estimates. In addition, the model test flow coefficient was modified and retained in the actual thrust computation as required by the nondimensional thrust group associated with the selected thrust datum. One ATF engine was instrumented to permit accessment of the mass flow inflow in the divergent section; these data were compared with the full scale estimated data and a modifier applied as required to the final gross thrust computation.

23. This step-by-step, building block procedure was retained in the final in-flight gross thrust computational routine, along with an engine-to-engine gross thrust coefficient variation provision, based on uninstalled sea level static test data of each particular flight test engine. Each of the solid boxes in figure 3 represents a table lookup in the computer program and each of the lookups can be outputted to permit manual accessment of the values used for the thrust computation.

24. The ATF testing was also used to establish engine airflow relationships, nonafterburning mixing pressure losses, and heat addition pressure losses in the afterburner. The afterburner pressure loss data were required to compute nozzle pressure ratios based on total pressure measured in the inlet of the afterburner. Sixty-three data points from ATF testing of one engine were used to refine the final computational routine. Gross thrust of the computational routine was matched to the measured thrust within ± 0.5 percent with an average bias of less than 0.1 percent. Airflow was matched to within ± 0.2 percent with an average bias of less than 0.1 percent. Engine-to-engine variation modifiers were determined from sea level static data of a second engine, and the ATF measured airflow and thrust data from this second engine were compared to computed altitude performance. Based on 14 data points, the computational routine predicted higher than actual gross thrust by 1.5 to 3 percent and predicted airflow to within ± 0.4 percent with an average bias of 0.2 percent. The net effect of these inaccuracies on net thrust with ± 2 percent compared with a predicted uncertainty in measured net thrust of ± 1.5 to ± 2.0 percent. The above discussion exemplifies the accuracies currently obtainable when special effort is made to identify detail variations between theoretical predictions and actual hardware performance.

TEST PLANNING GUIDELINES

INTEGRATED PROGRAM PLAN

25. The success achieved from a test program is directly related to the degree of attention given to details early in the planning phase of the overall development program. Early involvement of both propulsion system ground test specialist and flight test specialist will enhance the potential for successfully meeting the desired ground and flight test goals. General test program goals, applicable to both the ground and flight test programs, are:

a. To substantiate that the design performance capabilities of the propulsion system and propulsion system/airframe combination have been met.

b. To provide information for assessment of departures from design goals and identify the causes of departures.

c. To provide information which will permit accurate prediction of performance variations resulting from design changes which occur during the operational life cycle of the airframe and propulsion system.

d. To provide information which can be feedback to the designer and used to substantiate and enhance theoretical estimation techniques.

e. To provide a data base for improvement of future designs.

The test programs, data acquisition systems, and data reduction procedures must be structured to meet these goals. A successful approach for achieving this requirement has been the use of a task force concept involving all the various specialists involved with the development, test, and evaluation of both the propulsion system and the airframe/propulsion system combination. Formation of the task force should be accomplished to insure proper integration of the following:

f. Model, rig, and full scale propulsion system test programs.

g. Airframe wind tunnel test programs.

h. Selection of airframe and propulsion system test instrumentation.

i. Selection of the in-flight thrust computational method.

j. Data handling procedures used for both the propulsion system ground tests and airframe/propulsion system flight tests.

An integrated planned approach should be formulated by the task force and responsibilities assigned for prosecution of the plan. Periodic meetings of the task force should be held to review progress and update the plan as required.

SELECTION OF METHOD

26. Selection of a method for computing in-flight thrust is made predicted on the particular circumstances of the specific program. Factors which should be considered in this selection are:

a. The scope and nature of the flight test program as dictated by the applicable flight test goals.

b. The known state-of-the-art accuracies obtainable from each of the candidate methods as applied to the type of propulsion system (turbojet or turbofan and nozzle type).

c. The economics of the particular situation as dictated by available resources relative to desired test goals.

27. The goals of the flight test program are a predominant factor which will influence the selection of a method for computing in-flight thrust. It is paramount that these goals be firmly established prior to any attempt to select an in-flight thrust computational method. Predicted design performance capability of the propulsion system/airframe combination is made based on drag estimates of the airframe and propulsion system thrust estimates. The design performance capability of the propulsion system/airframe combination can be substantiated without specific knowledge of propulsion system thrust and airframe drag. However, if the goal of the flight test program is to provide information for explicit assessment of departures from the design goals, then an in-flight thrust computational method which will provide accurate in-flight thrust information is required. The cost involved with utilization of one particular in-flight method compared to another method must be weighted against the fidelity of the data obtainable from each of the methods and related to the explicitness of the desired departure assessment. Similarly, the necessity for providing high fidelity information for enhancement of theoretical estimation techniques, and the size and quality of the data base to be generated for assessment of design changes and improvement of future designs, must be considered along with available resources in the selection of an in-flight thrust computational method.

SUMMARY

28. Several recent development programs have demonstrated that reasonably accurate in-flight thrust can be determined from the flight test data. The uncertainty associated with in-flight thrust calculations has been minimized using existing technology and carefully applying detailed analysis and procedures to identify the causes for variations between predicted and actual propulsion system performance. The key to the success of these programs has been attributed to the care taken during development of the in-flight thrust computational routine with emphasis placed on attention to details and a thorough understanding of the exhaust nozzle expansion process.

29. The information presented herein is provided to acquaint the flight test project engineer with a general understanding and appreciation for:

a. The historical background of the in-flight thrust determination problem.

b. Classical nozzle theory including ideal gross thrust and classical nozzle coefficients.

c. An example of a comprehensive approach used recently to develop an in-flight thrust computational routine starting with theoretical predictions, which were first modified by model test results (adjust to full scale) and then by full scale ATF engine test data.

d. The approach used to plan and implement development of in-flight computational routines for several recent successful full scale development programs.

LIST OF SYMBOLS

A	Area
C_D	Flow or Discharge Coefficient
C_G	Gross Thrust Coefficient
C_F	Ratio Measured to Ideal Gross Thrust
C_V	Velocity Coefficient for Ideal Convergent-Divergent Nozzle
C_X	Velocity Coefficient for Ideal Convergent Nozzle
F_G	Gross Thrust
F_N	Net Thrust
F_R	Ram Drag
NPR	Nozzle Pressure Ratio (P_{T_7}/P_{S_0})
P	Pressure
R	Gas Constant
T	Temperature
V	Velocity
W	Mass Flow
γ	Specific Heat Ratio

Subscripts

act	actual
av	average
con	convergent
con-div	convergent-divergent
eff	effective
id	ideal
S	static
t	total

Nozzle Station Notation

0	Free stream
7	Nozzle inlet
8	Nozzle throat
9	Nozzle exit

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